THE DISK-HALO CONNECTION AND THE NATURE

OF THE INTERSTELAR MEDIUM

Colin A. Norman

The Johns Hopkins University

and

Space Telescope Science Institute

Satoru Ikeuchi

Tokyo Astronomical Observatory

2. SUPERBUBBLE EVOLUTION AND STATISTICS

In the initial stages a superbubble will expand as a standard bubble solution with a continuous energy input with spherical geometry (Tomisaka *et al.* 1981) however, as the bubble propagates through a scale height or so of an exponential atmosphere it will accelerate down the rapidly decreasing pressure gradient and break out of the disk with an opening angle given (in radians) by the inverse of the Mach number at the point of break out. The resulting structure is a wide angle jet or chimney acting as a conduit for material to flow from the disk to the halo (Tomisaka and Ikeuchi 1986, MacLow and McRay 1987).

The number of superbubbles at any given time in the Galaxy has been estimated by Ikeuchi (1987) using the available data on the number of OB associations in the Galaxy and the average number of supernovae of type II per typical OB association. He finds a superbubble formation rate of order 10^{-4} per year and with an estimated lifetime of ten million years per superbubble one expects the steady state number of superbubbles in the Galaxy to be of order a thousand.

The filling factor of this hot superbubble generated gas is of order ten per cent of the total volume for the numbers given above. Of course this filling factor will increase for a larger and less clumped supernova rate and this could occur at an earlier phase of the evolution of the Galaxy or in galaxies of different types. We shall return to this question later.

Chimneys supply energy to the halo at a rate of order 10^{40}-10^{42} erg s^{-1}. The mass supply rate is of order a solar mass per year. The scale height of the hot component is of order a few kiloparsecs and after a cooling time of order 10^7 yr, gas in the halo can cool, condense and infall with a velocity of order ~ 200 kms^{-1}.

Generally a large scale mass circulation is set up with a commensurate energy and momentum input into the halo from superbubbles. As the gas rains back down onto the disk there will be a further exchange of mass energy and momentum—this time from the halo to the disk. Chimneys should be observed as independent entities from hard X-ray measurements in our own Galaxy and from absorption line studies, HI observations, etc. of external galaxies.

3. THE MULTIPHASE STRUCTURE OF THE DISK

Many of the details of our calculations will be presented elsewhere (Norman and Ikeuchi 1988). Here we will sketch qualitatively some of our basic results. A particularly important parameter to determine is the extent to which the hot component of gas is more or less all pervasive or merely occupies a small part of the volume of the overall disk interstellar medium. This property is described by the filling factor.

One way to look at this is to study the dependence of filling factor on the clumping of supernovae which is of course intimately related to the number and strength of the resulting superbubbles. It is convenient to include the analysis of the dependence of this parameter with mean ambient density. Normalising to an average power injected into the interstellar medium of order 10^{42} erg s^{-1} we find that the Galaxy has a filling factor of about 10% for the hot gas component. In fact, this is exactly the region in parameter space where the chimney model applies. The standard McKee–Ostriker model seems more applicable to systems with ambient densities and superbubble rates lower by about an order of magnitude each. A two-phase model (c.f. Field 1986) will be relevant to galaxies

with significantly higher densities than would be found in later type galaxies. Clearly the chimney model has pleasing aspects of both the two and three phase models—it is essentially a two phase model with the third hot phase being the the hot chimneys with their current Galactic filling factor of about 10%.

For recent overviews of our knowledge of the interstellar medium in both halos and disks and flows from disk to halo one should consult the books by Bregman and Lockman (1986), Hollenbach and Thronson (1987) and the recent preprint by Corbelli and Salpeter (1987). We can also study the global mass and energy flow from the disk to the halo. One important physical point is to determine whether or not conditions are suitable for the superbubbles to burst out of the disk into the halo. This is a crucial part of the chimney picture. We find that for canonical Galactic parameters the chimney phase is associated with a mass flow rate of 0.3-3 $M_\odot$ yr^{-1} and a global power input of 10^{40}–10^{42} erg s^{-1}. These numbers which emerge naturally from the calculation are those conventionally thought to apply to the Galaxy and give us additional confidence in the applicability of the chimney model to the Galaxy.

4. THE STRUCTURE OF THE HALO

Our halo model is one where most of the physical quantities circulate: mass, metallicity, and magnetic field, for example. The circulation does not start directly from the disk as in other models. The mass flow, for example, is injected at a distance from the disk of approximately 1 kpc as the chimney structure widens appreciably and the material is subsequently injected into upper halo. In the upper halo, significant—more or less complete—mixing occurs. Cooling takes place and the mass can rain back down on the disk. Note that in this case the temperature increases with scale height in distinction to some other models. This overall mass flow can eventually be determined observationally by using the full range of measurements available including neutral hydrogen studies in both emission and absorption of the gas distribution and its kinematics, X-ray measurements in both the hard and soft energy bands, and quasar absorption line studies. Radio continuum studies of the thermal and non-thermal distribution and its spectral index variation are also potentially important indicators of the size and distribution of shock waves propagating into the halo.

It is important to emphasise that in this model the halo is in a crucial even prima donna role regulating the overall pressure balance, and mass and energy flow between the halo and the disk. In many ways it has a similar physical role as the all pervading hot gas in the McKee-Ostriker model. The connectivity of the hot gas is not, however in the disk, but via the chimneys and general halo gas (Figure 1).

5. FURTHER IMPLICATIONS AND SUMMARY

This model has some interesting implications for our understanding of quasar absorption lines, the dynamo mechanism in spiral galaxies, the nature of cosmic rays, the structure of edge on galaxies, and the nature of interstellar media in external galaxies.

The interpretation of quasar absorption lines depends on our understanding of the evolution of the intervening galactic interstellar media and hot gaseous coronae as a function

of cosmic time. Halos can evolve quite significantly from, perhaps, enormous wind driven structures at early epochs to chimney driven coronae, and in some cases to cooling halos where the supernova rate drops below the critical value for the blowout condition to be satisfied. One could envision an early stage of extended high ionisation followed by a slow shrinking of the halo through the CIV stage to the coooler MgII phase. Many details are as yet unclear but a two pronged attack on both the interstellar medium and quasar will be increasingly productive (Figure 2).

In the chimney mode the galactic dynamo models may have to be significantly modified. Bouyancy may no longer be the dominant mechanism for vertical magnetic flux transport. Here the magnetic flux is transported into the halo by an essentially convective mode in conjunction with the hot gas ejected through chimneys formed from superbubbles. The whole problem of cosmic ray acceleration and propagation is also altered significantly in this picture.

Chimneys should be observable in nearby galaxies. The problem is similar to that of finding a Heiles-type supershell in say M31. One very interesting observation relating to both edge on galaxies and the galactic dynamo problem is to determine whether or not the vertical component of the galactic magnetic field changes sign across the disk or not. In other words it would be most interesting to know whether the galactic dynamo is, in fact even or odd.

Some preliminary statements can be made on the nature of interstellar media in other galaxies. Very crude estimates of the mean ambient gas density and the power and clumpiness of supernovae in disk galaxies as a function of Hubble type can be used to infer the state of the phases of the interstellar medium as a function of Hubble type. Using a fairly broad brush, the picture is one where galaxies of type SO/Sa have a homogeneous three phase medium, the chimney model is relevant to galaxies of type Sb/Sc and for the later types, Sc/Irr, the predominant state of the interstellar medium is expected to be two phase.
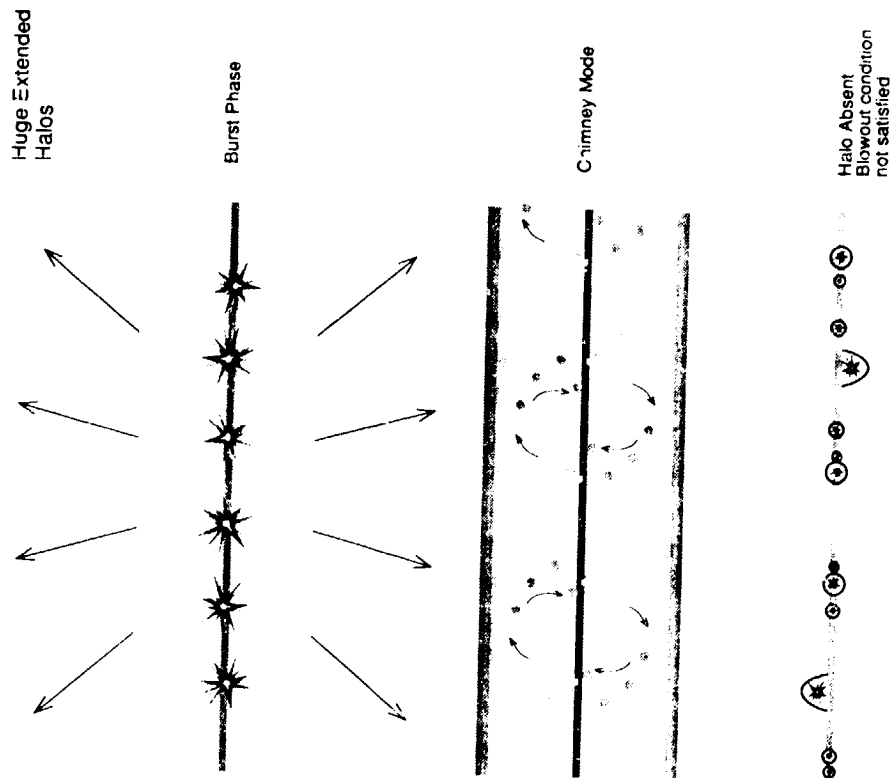
We have presented our attempt to incorporate in models of the gaseous component of both halo and disk some of the recent results on the nature of superbubbles and their substantial influence on the physics of the interstellar medium. We have described qualitively how crucial the mass and energy flow through the halo is for the disk component as well as the halo gas. A number of implications have been discussed and the variation of the phases of the interstellar medium with Hubble-type briefly noted.
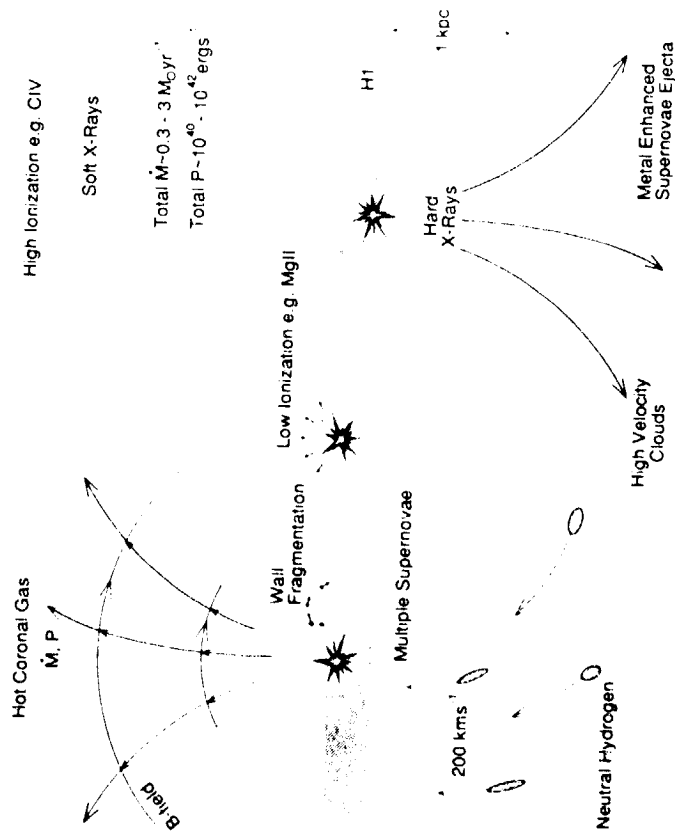
Acknowledgements

REFERENCES

Bregman, J. N. 1980 *Ap. J.*, **236**, 577.

Bregman, J. N. and Lockman, J. 1986, Gaseous Halos of Galaxies (NRAO)

Brinks, E. 1984, PhD Thesis, University of Leiden.

Corbelli, E. and Salpeter, E. E. 1987 *Ap. J.*, in press.

Cox, D. and Reynolds, R. 1987, preprint.

Field, G. B. 1986 in *Highlights of Modern Astrophysics: Concepts and Controversies*, eds.
S. L. Shapiro and S. A. Teukolsky (John Wiley and Sons).

Heckman,T. M., Armus, L. and Miley, G. K. 1987, *A. J.*, **93**, 264.

Hollenbach, D. and Thronson, H. A. 1987 *Interstellar Processes* (Reidel).

Ikeuchi, S. 1987 in *Star Formation in Galaxies*, eds. T. X. Thuan and T. Montmerle.

Kulkarni, S. R. and Heiles, C. 1987 in *Galactic and Extragalactic Radio Astronomy*, eds.
K. I. Kellerman and G. L. Verschuur, in press.

MacLow, M. and McRay, R. 1987 *Ap. J.*, in press.

McKee, C. F. and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148.

Norman, C. A. and Ikeuchi, S. 1988, in preparation.

Tomisaka, K., Habe, A., and Ikeuchi, S. 1981, *Ap. Sp. Sci.*, **78**, 273.

Tomisaka, K., and Ikeuchi, S. 1987, *Publ. Astron. Soc. Japan*, **38**, 697.

Huge Extended Halos

Burst Phase

Chimney Mode

Halo Absent
Blowout condition
not satisfied

HALO EVOLUTION

FIGURE 2

High Ionization e.g. CIV

Soft X-Rays

Total $\dot{M} \sim 0.3 - 3\ M_\odot yr^{-1}$
Total $P \sim 10^{40} - 10^{42}$ ergs

1 kpc

H1

Hard
X-Rays

Metal Enhanced
Supernovae Ejecta

High Velocity
Clouds

Hot Coronal Gas
$\dot{M}$, P

Wall
Fragmentation

Low Ionization e.g. MgII

Multiple Supernovae

B field

200 kms⁻¹

Neutral Hydrogen

HALO STRUCTURE

FIGURE 1

7